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# Measurement of the $ZZ$ production cross section and limits on anomalous neutral triple gauge couplings in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

(The ATLAS Collaboration)

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A measurement of the  $ZZ$  production cross section in proton-proton collisions at  $\sqrt{s} = 7$  TeV using data recorded by the ATLAS experiment at the LHC is presented. In a data sample corresponding to an integrated luminosity of  $1.02 \text{ fb}^{-1}$  collected in 2011, 12 events containing two  $Z$  boson candidates decaying to electrons and/or muons are observed. The expected background contribution is  $0.3 \pm 0.3(\text{stat.})_{-0.3}^{+0.4}(\text{syst.})$  events. The cross section measured in a phase-space region with good detector acceptance and for dilepton masses within the range 66 GeV to 116 GeV is  $\sigma_{ZZ \rightarrow \ell^+ \ell^- \ell^+ \ell^-}^{\text{fid}} = 19.4_{-5.2}^{+6.3}(\text{stat.})_{-0.7}^{+0.9}(\text{syst.}) \pm 0.7(\text{lumi.}) \text{ fb}$ . This result is then used to derive the total cross section for on-shell  $ZZ$  production,  $\sigma_{ZZ}^{\text{tot}} = 8.5_{-2.3}^{+2.7}(\text{stat.})_{-0.3}^{+0.4}(\text{syst.}) \pm 0.3(\text{lumi.}) \text{ pb}$ , which is consistent with the Standard Model expectation of  $6.5_{-0.2}^{+0.3} \text{ pb}$  calculated at the next-to-leading order in QCD. Limits on anomalous neutral triple gauge boson couplings are derived.

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The production of pairs of  $Z$  bosons at the LHC is of great interest since it provides an excellent opportunity to test the predictions of the electroweak sector of the Standard Model at the TeV energy scale; moreover it is the irreducible background to the search for the Higgs boson in the  $H \rightarrow ZZ$  decay channel. In the Standard Model,  $ZZ$  production proceeds at leading order (LO) via  $t$ -channel quark-antiquark interactions; the  $ZZZ$  and  $ZZ\gamma$  neutral triple gauge boson couplings (nTGCs) are absent, hence there is no contribution from  $s$ -channel  $q\bar{q}$  annihilation at tree level. At the one-loop level, fermion triangles generate nTGCs of  $\mathcal{O}(10^{-4})$  [1]. Many models of physics beyond the Standard Model predict values of nTGCs at the level of  $10^{-4}$  to  $10^{-3}$  [2]. The signature of non-zero nTGCs is an increase of the  $ZZ$  cross section at high  $ZZ$  invariant mass and high transverse momentum of the  $Z$  bosons [3].  $ZZ$  production has been studied in  $e^+e^-$  collisions at LEP [4, 5] and in  $p\bar{p}$  collisions at the Tevatron [6, 7]. No deviation of the measured cross section from the Standard Model expectation has been observed, and limits on anomalous nTGCs have been set [5, 6].

This letter presents the first measurement of  $ZZ$  [8] production in proton-proton collisions at a centre-of-mass energy  $\sqrt{s}$  of 7 TeV, and limits on the anomalous nTGCs. The cross section for on-shell  $ZZ$  production (i.e. in the zero-width approximation) is predicted at next-to-leading order (NLO) in QCD to be  $6.5_{-0.2}^{+0.3} \text{ pb}$  [9]; this includes a  $\sim 6\%$  contribution from gluon fusion. Candidate  $ZZ$  events are reconstructed in the  $ZZ \rightarrow \ell^+ \ell^- \ell^+ \ell^-$  decay channel, where  $\ell$  can be an electron or muon. Although this channel constitutes only  $\sim 0.5\%$  of the total  $ZZ$  cross section, its final state with four high transverse-momentum, isolated leptons has a very high expected signal to background ratio of  $\sim 30$ .

To reduce systematic uncertainties, the cross section is measured within a phase-space that corresponds closely to the experimental acceptance; this is termed the ‘fiducial’ cross section. The fiducial phase-space definition

requires the invariant mass of both lepton pairs to be between 66 GeV and 116 GeV and all four leptons to be within the pseudorapidity [10] range  $|\eta| < 2.5$  and have transverse momentum  $p_T > 15 \text{ GeV}$ . The four-momenta of all photons present after the simulation of the parton shower which are within  $\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.1$  of a lepton are summed into the four momentum of that lepton. The total  $ZZ$  cross section in the on-shell approximation is obtained from the fiducial cross section using the known  $Z \rightarrow \ell^+ \ell^-$  branching ratio and a correction factor for the kinematic and geometrical acceptance.

Anomalous nTGCs for on-shell  $ZZ$  production can be parameterized by two CP-violating ( $f_4^V$ ) and two CP-conserving ( $f_5^V$ ) complex parameters ( $V = Z, \gamma$ ) which are zero in the Standard Model [3]. To ensure partial-wave unitarity, a form-factor parameterization is introduced to cause the couplings to vanish at high parton centre-of-mass energy  $\sqrt{\hat{s}}$ :  $f_i^V = f_{i0}^V / (1 + \hat{s}/\Lambda^2)^n$ . Here,  $\Lambda$  is the energy scale at which physics beyond the Standard Model will be directly observable,  $f_{i0}^V$  are the low-energy approximations of the couplings, and  $n$  is the form-factor power. Following Ref. [3],  $n = 3$  and  $\Lambda = 2 \text{ TeV}$  are chosen, so that expected limits are within the values provided by unitarity at LHC energies. The results with energy cutoff  $\Lambda = \infty$  are also presented as a comparison in the unitarity violation scheme.

The ATLAS detector [11] consists of inner tracking devices surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters and a muon spectrometer with a toroidal magnetic field. The inner detector, in combination with the 2 T field from the solenoid, provides precision tracking of charged particles for  $|\eta| < 2.5$ . It consists of a silicon pixel detector, a silicon strip detector and a straw tube tracker that also provides transition radiation measurements for electron identification. The calorimeter system covers the pseudorapidity range  $|\eta| < 4.9$ . It is composed of sampling calorimeters with either liquid argon (LAr) or scintillating tiles as the active media. In the region  $|\eta| < 2.5$  the electromagnetic LAr

calorimeter is finely segmented and plays an important role in electron identification. The muon spectrometer has separate trigger and high-precision tracking chambers which provide muon identification and measurement in  $|\eta| < 2.7$ .

A three-level trigger system selects events to be recorded for offline analysis. The events used in this analysis were selected with single-lepton triggers with nominal transverse momentum thresholds of 20 GeV for electrons and 18 GeV for muons. The efficiencies of the single-lepton triggers have been determined as a function of lepton  $p_T$  using large samples of  $Z \rightarrow \ell^+\ell^-$  events. The trigger efficiency for events passing the offline selection described below is 99.9% with an uncertainty of 0.1%.

This measurement uses a data sample of proton-proton collisions at  $\sqrt{s} = 7$  TeV recorded between February and June 2011. After data quality requirements, the total integrated luminosity used in the analysis is  $1.02 \text{ fb}^{-1}$ . The integrated luminosity uncertainty is 3.7% [12].

Events are required to contain a primary vertex formed from at least three associated tracks. The vertex with the largest sum of the  $p_T^2$  computed from the associated tracks is selected as the primary vertex.

Signal events are characterized by four high- $p_T$ , isolated electrons or muons, in three channels:  $e^+e^-e^+e^-$ ,  $\mu^+\mu^-\mu^+\mu^-$  and  $e^+e^-\mu^+\mu^-$ . Lepton candidates are required to be consistent with originating from the primary vertex. Muons are identified by matching tracks (or track segments) reconstructed in the muon spectrometer to tracks reconstructed in the inner detector [13]. Their momentum is calculated by combining the information from the two systems and correcting for the energy deposited in the calorimeters. Only muons with  $p_T > 15$  GeV and  $|\eta| < 2.5$  are considered. In order to reject muons from the decay of heavy quarks, isolated muons are selected by requiring the scalar sum of the transverse momenta ( $\Sigma p_T$ ) of other tracks with  $p_T > 1$  GeV inside a cone of size  $\Delta R = 0.2$  around the muon to be no more than 15% of the muon  $p_T$ . The overall reconstruction, identification and isolation efficiency, measured in data using a large sample of  $Z \rightarrow \mu^+\mu^-$  events, varies as a function of  $p_T$  from 92% at 15 GeV to 95% at 45 GeV.

Electrons are reconstructed from a cluster in the electromagnetic calorimeter matched to a track in the inner detector [13]. Electron candidates are required to pass the ‘medium’ identification criteria described in Ref. [13], to have a transverse momentum (measured in the calorimeter) of at least 15 GeV and a pseudorapidity of  $|\eta| < 2.47$ . They must be isolated, using the same criterion as for muons, calculating the  $\Sigma p_T$  around the electron track. Electron candidates within  $\Delta R = 0.1$  of any selected muon are rejected, and if two electron candidates are within  $\Delta R = 0.1$  of each other the one with the lower  $p_T$  is rejected. The overall reconstruction, identification and isolation efficiency varies as a function of  $p_T$  from 63% at 15 GeV to 81% at 45 GeV.

Selected events are required to have exactly four lep-

tons, and to have passed a single-muon or single-electron trigger. To ensure high trigger efficiency, at least one of these leptons must have  $p_T > 20$  GeV (25 GeV) for a muon (electron) and match to a muon (electron) reconstructed online by the trigger system within  $\Delta R < 0.1$  (0.15).

Same-flavour, oppositely-charged lepton pairs are combined to form  $Z$  candidates. An event must contain two such pairs. In the  $e^+e^-e^+e^-$  and  $\mu^+\mu^-\mu^+\mu^-$  channels, ambiguities are resolved by choosing the pairing which results in the smaller value of the sum of the two  $|m_{\ell\ell} - m_Z|$  values. Figure 1 shows the correlation between the invariant mass of the leading (higher  $p_T$ ) and the subleading (lower  $p_T$ ) lepton pair. The events cluster in the region where both masses are around  $m_Z$ . Events are required to contain two  $Z$  candidates with invariant masses satisfying  $66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$ .

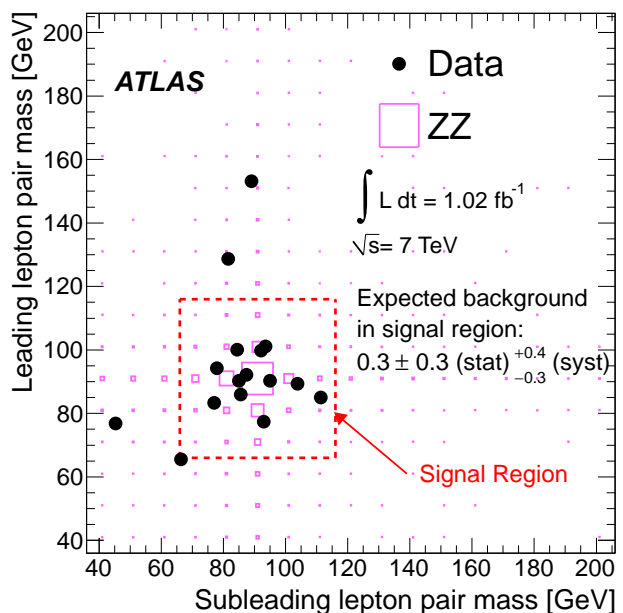


FIG. 1. The mass of the leading lepton pair versus the mass of the subleading lepton pair. The events observed in the data are shown as solid circles and the  $ZZ$  signal prediction from simulation as boxes. The large dashed box indicates the signal region defined by the requirements on the lepton-pair masses.

The reconstruction efficiency for  $ZZ$  events is determined from a detailed Monte Carlo simulation. The LO generator PYTHIA [14] with the MRST modified LO parton density function (PDF) set [15] is used to model  $pp \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$  events, where  $\ell$  includes electrons, muons and  $\tau$  leptons. The PYTHIA simulation includes the interference terms between the  $Z$  and  $\gamma^*$  diagrams; the mass threshold for the  $Z/\gamma$  boson is set to 12 GeV. The detector response is simulated [16] with a program based on GEANT4 [17]. Additional inelastic  $pp$  events are included in the simulation, distributed so as

to reproduce the number of collisions per bunch-crossing in the data. The simulation is also corrected with scale factors, and the lepton momentum resolution adjusted, to reproduce the lepton reconstruction and identification efficiencies measured in data.

The overall efficiencies of the reconstruction and selection criteria for events generated within the fiducial phase-space are  $(40\pm3)\%$ ,  $(79\pm2)\%$  and  $(57\pm2)\%$  for  $e^+e^-e^+e^-$ ,  $\mu^+\mu^-\mu^+\mu^-$  and  $e^+e^-\mu^+\mu^-$  respectively. The dominant systematic uncertainties arise from electron identification (6.6% in the  $e^+e^-e^+e^-$  final state, 3.1% in the  $e^+e^-\mu^+\mu^-$  final state) and from the muon reconstruction efficiency (2.0% in  $\mu^+\mu^-\mu^+\mu^-$  and 1.0% in  $e^+e^-\mu^+\mu^-$ ).

Background to the  $ZZ$  signal originates from events with a  $Z$  (or  $W^\pm$ ) boson decaying to leptons plus additional jets or photons ( $W/Z + X$ ), from top-quark production and from other diboson final states. Such events may contain electrons or muons from the decay of heavy-flavoured hadrons, or muons from in-flight decay of pions and kaons; jets or photons may be misidentified as electrons. The majority of these background leptons are rejected by the isolation requirement.

To estimate the background contribution from four-lepton events in which one lepton originates from a jet, a sample of events containing three leptons passing all selection criteria plus one ‘lepton-like jet’ is identified; such events are denoted  $\ell\ell\ell j$ . For muons, the lepton-like jets are muon candidates that fail the isolation requirement. For electrons, the lepton-like jets are clusters in the electromagnetic calorimeter matched to inner detector tracks that fail either or both of the full electron selection and the isolation requirement. The events are otherwise required to pass the full event selection, treating the lepton-like jet as if it were a fully identified lepton. This event sample is dominated by  $Z+X$  events. The background is then estimated by scaling this control sample by a measured factor  $f$  which is the ratio of the probability for a jet to satisfy the full lepton criteria to the probability to satisfy the lepton-like jet criteria. The background in which two selected leptons originate from jets is treated similarly, by identifying a data sample with two leptons and two lepton-like jets; such events are denoted  $\ell\ell jj$ . To avoid double counting in the background estimate, and to take into account the expected  $ZZ$  contribution in the control region,  $N(ZZ)$ , the total number of background events  $N(\text{BG})$  is calculated as:

$$N(\text{BG}) = N(\ell\ell\ell j) \times f - N(\ell\ell jj) \times f^2 - N(ZZ). \quad (1)$$

The factor  $f$  is measured in a sample of data selected with single-lepton triggers with criteria applied to suppress isolated leptons from  $W^\pm$  and  $Z$  bosons, and corrected for the remaining small contribution of true leptons using simulation. It is measured independently in  $\eta$  and  $p_T$  and the values combined assuming they are uncorrelated. A similar analysis is performed on Monte Carlo simulation of background processes; the larger of the statistical uncertainty on  $f$  determined from the data

TABLE I. Summary of observed events in the data, total background contributions and expected signal in the individual four-lepton and combined channels. The quoted uncertainties represent 68.3% confidence intervals; the first is statistical while the second is systematic. The uncertainties on the integrated luminosity (3.7%) and the theoretical  $ZZ$  cross section ( $^{+4.7\%}_{-3.1\%}$ ) are not included.

Channel	Observed	BG(data-driven)	Expected $ZZ$
$e^+e^-e^+e^-$	2	$0.01^{+0.03+0.05}_{-0.01-0.01}$	$1.53\pm0.03\pm0.10$
$\mu^+\mu^-\mu^+\mu^-$	8	$0.3 \pm 0.3 \pm 0.3$	$3.03\pm0.04\pm0.06$
$e^+e^-\mu^+\mu^-$	2	$< 0.01^{+0.03}_{-0.01}$	$4.37\pm0.04\pm0.14$
$\ell^+\ell^-\ell^+\ell^-$	12	$0.3 \pm 0.3^{+0.4}_{-0.3}$	$8.9\pm0.1\pm0.3$

and the difference between data and simulation is taken as the systematic uncertainty in each  $p_T$  (or  $\eta$ ) bin. This results in a systematic uncertainty which varies as a function of  $p_T$  from 57% (85%) at 15 GeV to 55% (77%) at 45 GeV for electrons (muons).

The numbers of expected and observed events after applying all selection criteria are shown in Table I. The expected number of signal events is determined from the PYTHIA simulation normalized to the NLO calculation using MCFM [9] with the MSTW2008 [18] NLO PDF set. The normalization factor, calculated within the phase-space of the fiducial cross section measurement, is 1.41. The expected numbers of signal events include contributions of 1.6% from  $ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$  events generated outside the fiducial phase-space and 0.3% from events where one of the  $Z$  bosons decays to  $\tau$  leptons. Twelve  $ZZ$  candidates are observed in data, with a background expectation of  $0.3 \pm 0.3(\text{stat.})^{+0.4}_{-0.3}(\text{syst.})$ , corresponding to a p-value of  $10^{-7}$  equivalent to a one-sided Gaussian significance of  $5\sigma$ . In the four-muon channel 8 events are observed where  $3.3^{+0.4}_{-0.3}$  signal plus background events are expected. The probability of the expected number fluctuating up to 8 or more is 3.2%.

The transverse momentum distribution and the invariant mass distribution of the combined four-lepton system for the selected candidates are shown in Fig. 2.

The  $ZZ$  fiducial cross section is determined using a maximum likelihood fitting method to combine the three four-lepton channels. The systematic uncertainties are included in the fitting procedure as nuisance parameters. The measured fiducial cross section is:

$$\sigma_{ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-}^{\text{fid}} = 19.4^{+6.3}_{-5.2}(\text{stat.})^{+0.9}_{-0.7}(\text{syst.}) \pm 0.7(\text{lumi.})\text{fb},$$

where  $\ell^+\ell^-\ell^+\ell^-$  refers to the sum of the  $e^+e^-e^+e^-$ ,  $e^+e^-\mu^+\mu^-$  and  $\mu^+\mu^-\mu^+\mu^-$  final states. The total cross section is determined similarly, correcting for the known  $Z \rightarrow \ell^+\ell^-$  branching ratios and the acceptance of the fiducial phase-space. This acceptance, calculated at NLO using MCFM version 6.0 with the MSTW2008 PDF set, is  $0.507 \pm 0.009$ , where the error arises primarily from PDF uncertainties with a 1% contribution from QED radiative corrections and off-shell  $Z/\gamma^*$  effects evaluated

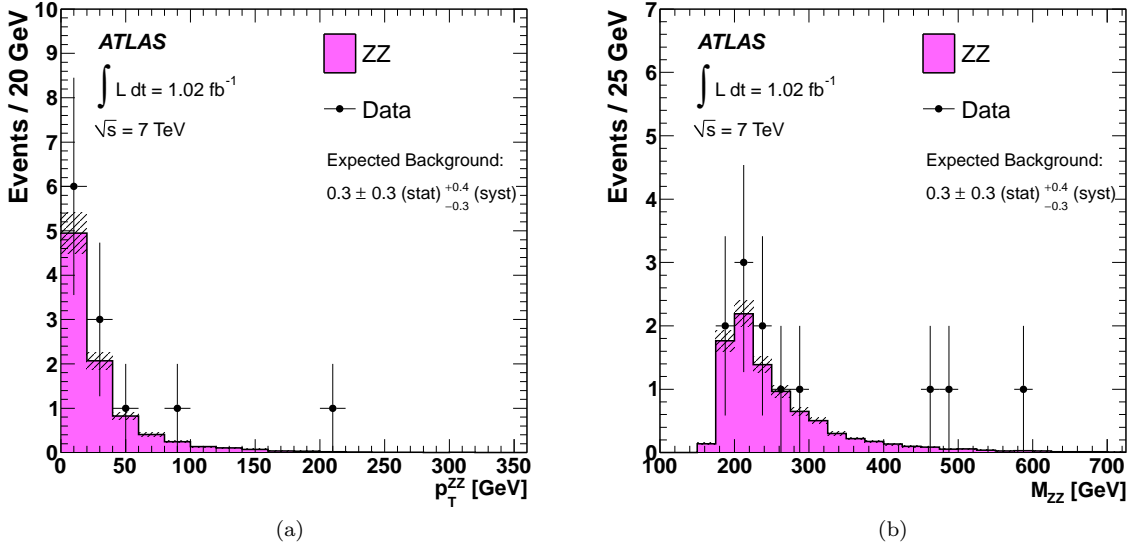


FIG. 2. (a) Transverse momentum  $p_T^{ZZ}$  and (b) invariant mass  $M_{ZZ}$  of the four-lepton system for the selected events. The points represent the observed data and the histograms show the signal prediction from simulation. The shaded band on each histogram shows the combined statistical and systematic uncertainty on the signal prediction. The predicted number of background events from the data-driven background estimate is indicated on the plot.

TABLE II. One dimensional 95% confidence intervals for anomalous neutral gauge boson couplings, where the limit for each coupling assumes the other couplings fixed at their Standard Model value. Limits are presented for form factor scales of  $\Lambda = 2$  TeV and  $\Lambda = \infty$  and include both statistical and systematic uncertainties; the statistical uncertainties are dominant.

$\Lambda$	$f_{40}^\gamma$	$f_{40}^Z$	$f_{50}^\gamma$	$f_{50}^Z$
2 TeV	$[-0.15, 0.15]$	$[-0.12, 0.12]$	$[-0.15, 0.15]$	$[-0.13, 0.13]$
$\infty$	$[-0.08, 0.08]$	$[-0.07, 0.07]$	$[-0.08, 0.08]$	$[-0.07, 0.07]$

from POWHEG BOX [19]. The measured value of the total on-shell  $ZZ$  cross section is:

$$\sigma_{ZZ}^{\text{tot}} = 8.5_{-2.3}^{+2.7} (\text{stat.}) {}_{-0.3}^{+0.4} (\text{syst.}) \pm 0.3 (\text{lumi.}) \text{ pb.}$$

The result is consistent within errors with the NLO Standard Model total cross section for this process of  $6.5_{-0.2}^{+0.3}$  pb [9].

Limits on anomalous nTGCs are determined using the total number of observed events only. The  $ZZ$  production yield dependency on couplings is parameterized using fully simulated events generated with SHERPA [20] subsequently reweighted using the leading-order matrix element [3] within the framework of Ref. [21]. The reweighting procedure uses simulated samples with Standard Model as well as non-Standard Model coupling values to ensure adequate coverage of all kinematic regions. One dimensional 95% confidence intervals for the anomalous nTGCs are determined using a maximum profile

likelihood fit to the observed number of events. The systematic errors are included as nuisance parameters. The resulting limits for each coupling, determined assuming real couplings and with the other couplings fixed at their Standard Model value, are listed in Table II. The present results are dominated by statistical uncertainties: limits derived using statistical uncertainties alone differ from those in Table II by less than 0.01. These limits are comparable with, or are more stringent than, those derived from measurements at LEP [5] and the Tevatron [6]; it should be noted that limits from LEP do not use a form factor, and those from the Tevatron use  $\Lambda = 1.2$  TeV.

In summary, the  $ZZ$  production cross section has been measured in proton-proton collisions at  $\sqrt{s} = 7$  TeV using the ATLAS detector. Both the fiducial cross section within the detector acceptance and the total cross section have been determined. The latter is in agreement with the Standard Model expectation. Limits on anomalous nTGCs have been derived.

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# The ATLAS Collaboration

G. Aad<sup>48</sup>, B. Abbott<sup>111</sup>, J. Abdallah<sup>11</sup>, A.A. Abdelalim<sup>49</sup>, A. Abdesselam<sup>118</sup>, O. Abdinov<sup>10</sup>, B. Abi<sup>112</sup>, M. Abolins<sup>88</sup>, H. Abramowicz<sup>153</sup>, H. Abreu<sup>115</sup>, E. Acerbi<sup>89a,89b</sup>, B.S. Acharya<sup>164a,164b</sup>, D.L. Adams<sup>24</sup>, T.N. Addy<sup>56</sup>, J. Adelman<sup>175</sup>, M. Aderholz<sup>99</sup>, S. Adomeit<sup>98</sup>, P. Adragna<sup>75</sup>, T. Adye<sup>129</sup>, S. Aefsky<sup>22</sup>, J.A. Aguilar-Saavedra<sup>124b,a</sup>, M. Aharrouche<sup>81</sup>, S.P. Ahlen<sup>21</sup>, F. Ahles<sup>48</sup>, A. Ahmad<sup>148</sup>, M. Ahsan<sup>40</sup>, G. Aielli<sup>133a,133b</sup>, T. Akdogan<sup>18a</sup>, T.P.A. Åkesson<sup>79</sup>, G. Akimoto<sup>155</sup>, A.V. Akimov<sup>94</sup>, A. Akiyama<sup>67</sup>, M.S. Alam<sup>1</sup>, M.A. Alam<sup>76</sup>, J. Albert<sup>169</sup>, S. Albrand<sup>55</sup>, M. Aleksa<sup>29</sup>, I.N. Aleksandrov<sup>65</sup>, F. Alessandria<sup>89a</sup>, C. Alexa<sup>25a</sup>, G. Alexander<sup>153</sup>, G. Alexandre<sup>49</sup>, T. Alexopoulos<sup>9</sup>, M. Alhroob<sup>20</sup>, M. Aliev<sup>15</sup>, G. Alimonti<sup>89a</sup>, J. Alison<sup>120</sup>, M. Aliyev<sup>10</sup>, P.P. Allport<sup>73</sup>, S.E. Allwood-Spiers<sup>53</sup>, J. Almond<sup>82</sup>, A. Aloisio<sup>102a,102b</sup>, R. Alon<sup>171</sup>, A. Alonso<sup>79</sup>, B. Alvarez Gonzalez<sup>88</sup>, M.G. Alvigi<sup>102a,102b</sup>, K. Amako<sup>66</sup>, P. Amaral<sup>29</sup>, C. Amelung<sup>22</sup>, V.V. Ammosov<sup>128</sup>, A. Amorim<sup>124a,b</sup>, G. Amorós<sup>167</sup>, N. Amram<sup>153</sup>, C. Anastopoulos<sup>29</sup>, L.S. Ancu<sup>16</sup>, N. Andari<sup>115</sup>, T. Andeen<sup>34</sup>, C.F. Anders<sup>20</sup>, G. Anders<sup>58a</sup>, K.J. Anderson<sup>30</sup>, A. Andreazza<sup>89a,89b</sup>, V. Andrei<sup>58a</sup>, M.-L. Andrieux<sup>55</sup>, X.S. Anduaga<sup>70</sup>, A. Angerami<sup>34</sup>, F. Anghinolfi<sup>29</sup>, N. Anjos<sup>124a</sup>, A. Annovi<sup>47</sup>, A. Antonaki<sup>8</sup>, M. Antonelli<sup>47</sup>, A. Antonov<sup>96</sup>, J. Antos<sup>144b</sup>, F. Anulli<sup>132a</sup>, S. Aoun<sup>83</sup>, L. Aperio Bella<sup>4</sup>, R. Apolle<sup>118,c</sup>, G. Arabidze<sup>88</sup>, I. Aracena<sup>143</sup>, Y. Arai<sup>66</sup>, A.T.H. Arce<sup>44</sup>, J.P. Archambault<sup>28</sup>, S. Arfaoui<sup>83</sup>, J.-F. Arguin<sup>14</sup>, E. Arik<sup>18a,\*</sup>, M. Arik<sup>18a</sup>, A.J. Armbruster<sup>87</sup>, O. Arnaez<sup>81</sup>, A. Artamonov<sup>95</sup>, G. Artoni<sup>132a,132b</sup>, D. Arutinov<sup>20</sup>, S. Asai<sup>155</sup>, R. Asfandiyarov<sup>172</sup>, S. Ask<sup>27</sup>, B. Åsman<sup>146a,146b</sup>, L. Asquith<sup>5</sup>, K. Assamagan<sup>24</sup>, A. Astbury<sup>169</sup>, A. Astvatsatourov<sup>52</sup>, G. Atoian<sup>175</sup>, B. Aubert<sup>4</sup>, E. Auge<sup>115</sup>, K. Augsten<sup>127</sup>, M. Aurousseau<sup>145a</sup>, G. 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Bernius<sup>24</sup>, T. Berry<sup>76</sup>, A. Bertin<sup>19a,19b</sup>, F. Bertinelli<sup>29</sup>, F. Bertolucci<sup>122a,122b</sup>, M.I. Besana<sup>89a,89b</sup>, N. Besson<sup>136</sup>, S. Bethke<sup>99</sup>, W. Bhimji<sup>45</sup>, R.M. Bianchi<sup>29</sup>, M. Bianco<sup>72a,72b</sup>, O. Biebel<sup>98</sup>, S.P. Bieniek<sup>77</sup>, K. Bierwagen<sup>54</sup>, J. Biesiada<sup>14</sup>, M. Biglietti<sup>134a,134b</sup>, H. Bilokon<sup>47</sup>, M. Bindi<sup>19a,19b</sup>, S. Binet<sup>115</sup>, A. Bingul<sup>18c</sup>, C. Bini<sup>132a,132b</sup>, C. Biscarat<sup>177</sup>, U. Bitenc<sup>48</sup>, K.M. Black<sup>21</sup>, R.E. Blair<sup>5</sup>, J.-B. Blanchard<sup>115</sup>, G. Blanchot<sup>29</sup>, T. Blazek<sup>144a</sup>, C. Blocker<sup>22</sup>, J. Blocki<sup>38</sup>, A. Blondel<sup>49</sup>, W. Blum<sup>81</sup>, U. Blumenschein<sup>54</sup>, G.J. Bobbink<sup>105</sup>, V.B. Bobrovnikov<sup>107</sup>, S.S. Bocchetta<sup>79</sup>, A. Bocci<sup>44</sup>, C.R. 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Cerutti<sup>47</sup>, S.A. Cetin<sup>18b</sup>, F. Cevenini<sup>102a,102b</sup>, A. Chafaq<sup>135a</sup>, D. Chakraborty<sup>106</sup>, K. Chan<sup>2</sup>, B. Chapleau<sup>85</sup>, J.D. Chapman<sup>27</sup>, J.W. Chapman<sup>87</sup>, E. Chareyre<sup>78</sup>, D.G. Charlton<sup>17</sup>, V. Chavda<sup>82</sup>, C.A. Chavez Barajas<sup>29</sup>, S. Cheatham<sup>85</sup>, S. Chekanov<sup>5</sup>, S.V. Chekulaev<sup>159a</sup>, G.A. Chelkov<sup>65</sup>, M.A. Chelstowska<sup>104</sup>, C. Chen<sup>64</sup>, H. Chen<sup>24</sup>, S. Chen<sup>32c</sup>, T. Chen<sup>32c</sup>, X. Chen<sup>172</sup>, S. Cheng<sup>32a</sup>, A. Cheplakov<sup>65</sup>, V.F. Chepurinov<sup>65</sup>, R. Cherkaoui El Moursli<sup>135e</sup>, V. Chernyatin<sup>24</sup>, E. Cheu<sup>6</sup>, S.L. Cheung<sup>158</sup>, L. Chevalier<sup>136</sup>, G. Chiefari<sup>102a,102b</sup>, L. Chikovani<sup>51a</sup>, J.T. Childers<sup>58a</sup>, A. Chilingarov<sup>71</sup>, G. Chiodini<sup>72a</sup>, M.V. Chizhov<sup>65</sup>, G. Choudalakis<sup>30</sup>, S. Chouridou<sup>137</sup>, I.A. Christidi<sup>77</sup>, A. Christov<sup>48</sup>, D. Chromek-Burckhart<sup>29</sup>, M.L. Chu<sup>151</sup>, J. Chudoba<sup>125</sup>, G. Ciapetti<sup>132a,132b</sup>, K. Ciba<sup>37</sup>, A.K. Ciftci<sup>3a</sup>, R. Ciftci<sup>3a</sup>, D. Cinca<sup>33</sup>, V. Cindro<sup>74</sup>, M.D. Ciobotaru<sup>163</sup>, C. Ciocca<sup>19a</sup>, A. Ciocio<sup>14</sup>, M. Cirilli<sup>87</sup>, M. Ciubancan<sup>25a</sup>, A. Clark<sup>49</sup>, P.J. Clark<sup>45</sup>, W. Cleland<sup>123</sup>, J.C. Clemens<sup>83</sup>, B. Clement<sup>55</sup>, C. Clement<sup>146a,146b</sup>, R.W. Clift<sup>129</sup>, Y. Coadou<sup>83</sup>, M. Cobal<sup>164a,164c</sup>, A. Coccaro<sup>50a,50b</sup>, J. Cochran<sup>64</sup>, P. Coe<sup>118</sup>, J.G. Cogan<sup>143</sup>, J. Coggeshall<sup>165</sup>, E. Cogneras<sup>177</sup>, C.D. Cojocaru<sup>28</sup>, J. Colas<sup>4</sup>, A.P. Colijn<sup>105</sup>, C. 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Weber<sup>54</sup>, A.R. Weidberg<sup>118</sup>, P. Weigell<sup>99</sup>, J. Weingarten<sup>54</sup>, C. Weiser<sup>48</sup>, H. Wellenstein<sup>22</sup>, P.S. Wells<sup>29</sup>, M. Wen<sup>47</sup>, T. Wenaus<sup>24</sup>, S. Wendler<sup>123</sup>, Z. Weng<sup>151,q</sup>, T. Wengler<sup>29</sup>, S. Wenig<sup>29</sup>, N. Wermes<sup>20</sup>, M. Werner<sup>48</sup>, P. Werner<sup>29</sup>, M. Werth<sup>163</sup>, M. Wessels<sup>58a</sup>, C. Weydert<sup>55</sup>, K. Whalen<sup>28</sup>, S.J. Wheeler-Ellis<sup>163</sup>, S.P. Whitaker<sup>21</sup>, A. White<sup>7</sup>, M.J. White<sup>86</sup>, S.R. Whitehead<sup>118</sup>, D. Whiteson<sup>163</sup>, D. Whittington<sup>61</sup>, D. Wicke<sup>174</sup>, F.J. Wickens<sup>129</sup>, W. Wiedenmann<sup>172</sup>, M. Wielders<sup>129</sup>, P. Wienemann<sup>20</sup>, C. Wigglesworth<sup>75</sup>, L.A.M. Wiik<sup>48</sup>, P.A. Wijeratne<sup>77</sup>, A. Wildauer<sup>167</sup>, M.A. Wildt<sup>41,n</sup>, I. Wilhelm<sup>126</sup>, H.G. Wilkens<sup>29</sup>, J.Z. Will<sup>98</sup>, E. Williams<sup>34</sup>, H.H. Williams<sup>120</sup>, W. Willis<sup>34</sup>, S. Willocq<sup>84</sup>, J.A. Wilson<sup>17</sup>, M.G. Wilson<sup>143</sup>, A. Wilson<sup>87</sup>, I. Wingerter-Seez<sup>4</sup>, S. Winkelmann<sup>48</sup>, F. Winklmeier<sup>29</sup>, M. Wittgen<sup>143</sup>, M.W. Wolter<sup>38</sup>, H. Wolters<sup>124a,g</sup>, W.C. Wong<sup>40</sup>, G. Wooden<sup>87</sup>, B.K. Wosiek<sup>38</sup>, J. Wotschack<sup>29</sup>, M.J. Woudstra<sup>84</sup>, K. Wraight<sup>53</sup>, C. Wright<sup>53</sup>, M. Wright<sup>53</sup>, B. Wrona<sup>73</sup>, S.L. Wu<sup>172</sup>, X. Wu<sup>49</sup>, Y. Wu<sup>32b,ab</sup>, E. Wulf<sup>34</sup>

R. Wunstorff<sup>42</sup>, B.M. Wynne<sup>45</sup>, S. Xella<sup>35</sup>, M. Xiao<sup>136</sup>, S. Xie<sup>48</sup>, Y. Xie<sup>32a</sup>, C. Xu<sup>32b,ac</sup>, D. Xu<sup>139</sup>, G. Xu<sup>32a</sup>, B. Yabsley<sup>150</sup>, S. Yacoub<sup>145b</sup>, M. Yamada<sup>66</sup>, H. Yamaguchi<sup>155</sup>, A. Yamamoto<sup>66</sup>, K. Yamamoto<sup>64</sup>, S. Yamamoto<sup>155</sup>, T. Yamamura<sup>155</sup>, T. Yamanaka<sup>155</sup>, J. Yamaoka<sup>44</sup>, T. Yamazaki<sup>155</sup>, Y. Yamazaki<sup>67</sup>, Z. Yan<sup>21</sup>, H. Yang<sup>87</sup>, U.K. Yang<sup>82</sup>, Y. Yang<sup>61</sup>, Y. Yang<sup>32a</sup>, Z. Yang<sup>146a,146b</sup>, S. Yanush<sup>91</sup>, Y. Yasu<sup>66</sup>, G.V. Ybeles Smit<sup>130</sup>, J. Ye<sup>39</sup>, S. Ye<sup>24</sup>, M. Yilmaz<sup>3c</sup>, R. Yoosofmiya<sup>123</sup>, K. Yorita<sup>170</sup>, R. Yoshida<sup>5</sup>, C. Young<sup>143</sup>, S. Youssef<sup>21</sup>, D. Yu<sup>24</sup>, J. Yu<sup>7</sup>, J. Yu<sup>112</sup>, L. Yuan<sup>32a,ad</sup>, A. Yurkewicz<sup>106</sup>, V.G. Zaets<sup>128</sup>, R. Zaidan<sup>63</sup>, A.M. Zaitsev<sup>128</sup>, Z. Zajacova<sup>29</sup>, Yo.K. Zalite<sup>121</sup>, L. Zanello<sup>132a,132b</sup>, P. Zarzhitsky<sup>39</sup>, A. Zaytsev<sup>107</sup>, C. Zeitnitz<sup>174</sup>, M. Zeller<sup>175</sup>, M. Zeman<sup>125</sup>, A. Zemla<sup>38</sup>, C. Zendler<sup>20</sup>, O. Zenin<sup>128</sup>, T. Ženiš<sup>144a</sup>, Z. Zenonos<sup>122a,122b</sup>, S. Zenz<sup>14</sup>, D. Zerwas<sup>115</sup>, G. Zevi della Porta<sup>57</sup>, Z. Zhan<sup>32d</sup>, D. Zhang<sup>32b,aa</sup>, H. Zhang<sup>88</sup>, J. Zhang<sup>5</sup>, X. Zhang<sup>32d</sup>, Z. Zhang<sup>115</sup>, L. Zhao<sup>108</sup>, T. Zhao<sup>138</sup>, Z. Zhao<sup>32b</sup>, A. Zhemchugov<sup>65</sup>, S. Zheng<sup>32a</sup>, J. Zhong<sup>118</sup>, B. Zhou<sup>87</sup>, N. Zhou<sup>163</sup>, Y. Zhou<sup>151</sup>, C.G. Zhu<sup>32d</sup>, H. Zhu<sup>41</sup>, J. Zhu<sup>87</sup>, Y. Zhu<sup>32b</sup>, X. Zhuang<sup>98</sup>, V. Zhuravlov<sup>99</sup>, D. Zieminska<sup>61</sup>, R. Zimmermann<sup>20</sup>, S. Zimmermann<sup>20</sup>, S. Zimmermann<sup>48</sup>, M. Ziolkowski<sup>141</sup>, R. Zitoun<sup>4</sup>, L. Živković<sup>34</sup>, V.V. Zmouchko<sup>128,\*</sup>, G. Zobernig<sup>172</sup>, A. Zoccoli<sup>19a,19b</sup>, Y. Zolnierowski<sup>4</sup>, A. Zsenei<sup>29</sup>, M. zur Nedden<sup>15</sup>, V. Zutshi<sup>106</sup>, L. Zwalinski<sup>29</sup>.

<sup>1</sup> University at Albany, Albany NY, United States of America

<sup>2</sup> Department of Physics, University of Alberta, Edmonton AB, Canada

<sup>3</sup> (a)Department of Physics, Ankara University, Ankara;

(b)Department of Physics, Dumlupinar University, Kutahya; (c)Department of Physics, Gazi University, Ankara; (d)Division of Physics, TOBB University of Economics and Technology, Ankara; (e)Turkish Atomic Energy Authority, Ankara, Turkey

<sup>4</sup> LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

<sup>5</sup> High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America

<sup>6</sup> Department of Physics, University of Arizona, Tucson AZ, United States of America

<sup>7</sup> Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America

<sup>8</sup> Physics Department, University of Athens, Athens, Greece

<sup>9</sup> Physics Department, National Technical University of Athens, Zografou, Greece

<sup>10</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

<sup>11</sup> Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain

<sup>12</sup> (a)Institute of Physics, University of Belgrade, Belgrade; (b)Vinca Institute of Nuclear Sciences,

Belgrade, Serbia

<sup>13</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway

<sup>14</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America

<sup>15</sup> Department of Physics, Humboldt University, Berlin, Germany

<sup>16</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

<sup>17</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

<sup>18</sup> (a)Department of Physics, Bogazici University, Istanbul; (b)Division of Physics, Dogus University, Istanbul; (c)Department of Physics Engineering, Gaziantep University, Gaziantep; (d)Department of Physics, Istanbul Technical University, Istanbul, Turkey

<sup>19</sup> (a)INFN Sezione di Bologna; (b)Dipartimento di Fisica, Università di Bologna, Bologna, Italy

<sup>20</sup> Physikalisches Institut, University of Bonn, Bonn, Germany

<sup>21</sup> Department of Physics, Boston University, Boston MA, United States of America

<sup>22</sup> Department of Physics, Brandeis University, Waltham MA, United States of America

<sup>23</sup> (a)Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b)Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c)Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d)Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil

<sup>24</sup> Physics Department, Brookhaven National Laboratory, Upton NY, United States of America

<sup>25</sup> (a)National Institute of Physics and Nuclear Engineering, Bucharest; (b)University Politehnica Bucharest, Bucharest; (c)West University in Timisoara, Timisoara, Romania

<sup>26</sup> Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

<sup>27</sup> Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

<sup>28</sup> Department of Physics, Carleton University, Ottawa ON, Canada

<sup>29</sup> CERN, Geneva, Switzerland

<sup>30</sup> Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America

<sup>31</sup> (a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

<sup>32</sup> (a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b)Department of Modern Physics, University of Science and Technology of China, Anhui; (c)Department of Physics, Nanjing University, Jiangsu; (d)High Energy Physics Group, Shandong University, Shandong, China

<sup>33</sup> Laboratoire de Physique Corpusculaire, Clermont

Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France

<sup>34</sup> Nevis Laboratory, Columbia University, Irvington NY, United States of America

<sup>35</sup> Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

<sup>36</sup> <sup>(a)</sup>INFN Gruppo Collegato di Cosenza;

<sup>(b)</sup>Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy

<sup>37</sup> Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland

<sup>38</sup> The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland

<sup>39</sup> Physics Department, Southern Methodist University, Dallas TX, United States of America

<sup>40</sup> Physics Department, University of Texas at Dallas, Richardson TX, United States of America

<sup>41</sup> DESY, Hamburg and Zeuthen, Germany

<sup>42</sup> Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

<sup>43</sup> Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany

<sup>44</sup> Department of Physics, Duke University, Durham NC, United States of America

<sup>45</sup> SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

<sup>46</sup> Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3, 2700 Wiener Neustadt, Austria

<sup>47</sup> INFN Laboratori Nazionali di Frascati, Frascati, Italy

<sup>48</sup> Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany

<sup>49</sup> Section de Physique, Université de Genève, Geneva, Switzerland

<sup>50</sup> <sup>(a)</sup>INFN Sezione di Genova; <sup>(b)</sup>Dipartimento di Fisica, Università di Genova, Genova, Italy

<sup>51</sup> <sup>(a)</sup>E.Andronikashvili Institute of Physics, Georgian Academy of Sciences, Tbilisi; <sup>(b)</sup>High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

<sup>52</sup> II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

<sup>53</sup> SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

<sup>54</sup> II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

<sup>55</sup> Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France

<sup>56</sup> Department of Physics, Hampton University, Hampton VA, United States of America

<sup>57</sup> Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America

<sup>58</sup> <sup>(a)</sup>Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(b)</sup>Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(c)</sup>ZITI Institut für technische

Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

<sup>59</sup> Faculty of Science, Hiroshima University, Hiroshima, Japan

<sup>60</sup> Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

<sup>61</sup> Department of Physics, Indiana University, Bloomington IN, United States of America

<sup>62</sup> Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

<sup>63</sup> University of Iowa, Iowa City IA, United States of America

<sup>64</sup> Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America

<sup>65</sup> Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia

<sup>66</sup> KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

<sup>67</sup> Graduate School of Science, Kobe University, Kobe, Japan

<sup>68</sup> Faculty of Science, Kyoto University, Kyoto, Japan

<sup>69</sup> Kyoto University of Education, Kyoto, Japan

<sup>70</sup> Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina

<sup>71</sup> Physics Department, Lancaster University, Lancaster, United Kingdom

<sup>72</sup> <sup>(a)</sup>INFN Sezione di Lecce; <sup>(b)</sup>Dipartimento di Fisica, Università del Salento, Lecce, Italy

<sup>73</sup> Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

<sup>74</sup> Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia

<sup>75</sup> Department of Physics, Queen Mary University of London, London, United Kingdom

<sup>76</sup> Department of Physics, Royal Holloway University of London, Surrey, United Kingdom

<sup>77</sup> Department of Physics and Astronomy, University College London, London, United Kingdom

<sup>78</sup> Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

<sup>79</sup> Fysiska institutionen, Lunds universitet, Lund, Sweden

<sup>80</sup> Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain

<sup>81</sup> Institut für Physik, Universität Mainz, Mainz, Germany

<sup>82</sup> School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

<sup>83</sup> CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

<sup>84</sup> Department of Physics, University of Massachusetts, Amherst MA, United States of America

<sup>85</sup> Department of Physics, McGill University, Montreal QC, Canada

<sup>86</sup> School of Physics, University of Melbourne, Victoria, Australia

<sup>87</sup> Department of Physics, The University of Michigan,



Ann Arbor MI, United States of America

<sup>88</sup> Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America

<sup>89</sup> <sup>(a)</sup>INFN Sezione di Milano; <sup>(b)</sup>Dipartimento di Fisica, Università di Milano, Milano, Italy

<sup>90</sup> B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus

<sup>91</sup> National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus

<sup>92</sup> Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America

<sup>93</sup> Group of Particle Physics, University of Montreal, Montreal QC, Canada

<sup>94</sup> P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia

<sup>95</sup> Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia

<sup>96</sup> Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia

<sup>97</sup> Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

<sup>98</sup> Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany

<sup>99</sup> Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

<sup>100</sup> Nagasaki Institute of Applied Science, Nagasaki, Japan

<sup>101</sup> Graduate School of Science, Nagoya University, Nagoya, Japan

<sup>102</sup> <sup>(a)</sup>INFN Sezione di Napoli; <sup>(b)</sup>Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy

<sup>103</sup> Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America

<sup>104</sup> Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands

<sup>105</sup> Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands

<sup>106</sup> Department of Physics, Northern Illinois University, DeKalb IL, United States of America

<sup>107</sup> Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia

<sup>108</sup> Department of Physics, New York University, New York NY, United States of America

<sup>109</sup> Ohio State University, Columbus OH, United States of America

<sup>110</sup> Faculty of Science, Okayama University, Okayama, Japan

<sup>111</sup> Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America

<sup>112</sup> Department of Physics, Oklahoma State University, Stillwater OK, United States of America

<sup>113</sup> Palacký University, RCPTM, Olomouc, Czech Republic

<sup>114</sup> Center for High Energy Physics, University of Oregon, Eugene OR, United States of America

<sup>115</sup> LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France

<sup>116</sup> Graduate School of Science, Osaka University, Osaka, Japan

<sup>117</sup> Department of Physics, University of Oslo, Oslo, Norway

<sup>118</sup> Department of Physics, Oxford University, Oxford, United Kingdom

<sup>119</sup> <sup>(a)</sup>INFN Sezione di Pavia; <sup>(b)</sup>Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy

<sup>120</sup> Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America

<sup>121</sup> Petersburg Nuclear Physics Institute, Gatchina, Russia

<sup>122</sup> <sup>(a)</sup>INFN Sezione di Pisa; <sup>(b)</sup>Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy

<sup>123</sup> Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America

<sup>124</sup> <sup>(a)</sup>Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal;

<sup>(b)</sup>Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain

<sup>125</sup> Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic

<sup>126</sup> Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic

<sup>127</sup> Czech Technical University in Prague, Praha, Czech Republic

<sup>128</sup> State Research Center Institute for High Energy Physics, Protvino, Russia

<sup>129</sup> Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

<sup>130</sup> Physics Department, University of Regina, Regina SK, Canada

<sup>131</sup> Ritsumeikan University, Kusatsu, Shiga, Japan

<sup>132</sup> <sup>(a)</sup>INFN Sezione di Roma I; <sup>(b)</sup>Dipartimento di Fisica, Università La Sapienza, Roma, Italy

<sup>133</sup> <sup>(a)</sup>INFN Sezione di Roma Tor Vergata; <sup>(b)</sup>Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy

<sup>134</sup> <sup>(a)</sup>INFN Sezione di Roma Tre; <sup>(b)</sup>Dipartimento di Fisica, Università Roma Tre, Roma, Italy

<sup>135</sup> <sup>(a)</sup>Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; <sup>(b)</sup>Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat;

<sup>(c)</sup>Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000;

<sup>(d)</sup>Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; <sup>(e)</sup>Faculté des Sciences, Université Mohammed V, Rabat, Morocco

<sup>136</sup> DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France

<sup>137</sup> Santa Cruz Institute for Particle Physics, University

of California Santa Cruz, Santa Cruz CA, United States of America

<sup>138</sup> Department of Physics, University of Washington, Seattle WA, United States of America

<sup>139</sup> Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

<sup>140</sup> Department of Physics, Shinshu University, Nagano, Japan

<sup>141</sup> Fachbereich Physik, Universität Siegen, Siegen, Germany

<sup>142</sup> Department of Physics, Simon Fraser University, Burnaby BC, Canada

<sup>143</sup> SLAC National Accelerator Laboratory, Stanford CA, United States of America

<sup>144</sup> <sup>(a)</sup> Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; <sup>(b)</sup> Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

<sup>145</sup> <sup>(a)</sup> Department of Physics, University of Johannesburg, Johannesburg; <sup>(b)</sup> School of Physics, University of the Witwatersrand, Johannesburg, South Africa

<sup>146</sup> <sup>(a)</sup> Department of Physics, Stockholm University; <sup>(b)</sup> The Oskar Klein Centre, Stockholm, Sweden

<sup>147</sup> Physics Department, Royal Institute of Technology, Stockholm, Sweden

<sup>148</sup> Department of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of America

<sup>149</sup> Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

<sup>150</sup> School of Physics, University of Sydney, Sydney, Australia

<sup>151</sup> Institute of Physics, Academia Sinica, Taipei, Taiwan

<sup>152</sup> Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel

<sup>153</sup> Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

<sup>154</sup> Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

<sup>155</sup> International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

<sup>156</sup> Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

<sup>157</sup> Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

<sup>158</sup> Department of Physics, University of Toronto, Toronto ON, Canada

<sup>159</sup> <sup>(a)</sup> TRIUMF, Vancouver BC; <sup>(b)</sup> Department of Physics and Astronomy, York University, Toronto ON, Canada

<sup>160</sup> Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan

<sup>161</sup> Science and Technology Center, Tufts University, Medford MA, United States of America

<sup>162</sup> Centro de Investigaciones, Universidad Antonio

Narino, Bogota, Colombia

<sup>163</sup> Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America

<sup>164</sup> <sup>(a)</sup> INFN Gruppo Collegato di Udine; <sup>(b)</sup> ICTP, Trieste; <sup>(c)</sup> Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

<sup>165</sup> Department of Physics, University of Illinois, Urbana IL, United States of America

<sup>166</sup> Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

<sup>167</sup> Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain

<sup>168</sup> Department of Physics, University of British Columbia, Vancouver BC, Canada

<sup>169</sup> Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada

<sup>170</sup> Waseda University, Tokyo, Japan

<sup>171</sup> Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

<sup>172</sup> Department of Physics, University of Wisconsin, Madison WI, United States of America

<sup>173</sup> Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

<sup>174</sup> Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

<sup>175</sup> Department of Physics, Yale University, New Haven CT, United States of America

<sup>176</sup> Yerevan Physics Institute, Yerevan, Armenia

<sup>177</sup> Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

<sup>a</sup> Also at Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal

<sup>b</sup> Also at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal

<sup>c</sup> Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

<sup>d</sup> Also at TRIUMF, Vancouver BC, Canada

<sup>e</sup> Also at Department of Physics, California State University, Fresno CA, United States of America

<sup>f</sup> Also at Fermilab, Batavia IL, United States of America

<sup>g</sup> Also at Department of Physics, University of Coimbra, Coimbra, Portugal

<sup>h</sup> Also at Università di Napoli Parthenope, Napoli, Italy

<sup>i</sup> Also at Institute of Particle Physics (IPP), Canada

<sup>j</sup> Also at Department of Physics, Middle East Technical University, Ankara, Turkey

<sup>k</sup> Also at Louisiana Tech University, Ruston LA, United States of America

<sup>l</sup> Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada

<sup>m</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

<sup>n</sup> Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany

<sup>o</sup> Also at Manhattan College, New York NY, United States of America

<sup>p</sup> Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

<sup>q</sup> Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China

<sup>r</sup> Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan

<sup>s</sup> Also at High Energy Physics Group, Shandong University, Shandong, China

<sup>t</sup> Also at Section de Physique, Université de Genève, Geneva, Switzerland

<sup>u</sup> Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal

<sup>v</sup> Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America

<sup>w</sup> Also at KFKI Research Institute for Particle and

Nuclear Physics, Budapest, Hungary

<sup>x</sup> Also at California Institute of Technology, Pasadena CA, United States of America

<sup>y</sup> Also at Institute of Physics, Jagiellonian University, Krakow, Poland

<sup>z</sup> Also at Department of Physics, Oxford University, Oxford, United Kingdom

<sup>aa</sup> Also at Institute of Physics, Academia Sinica, Taipei, Taiwan

<sup>ab</sup> Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

<sup>ac</sup> Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique), Gif-sur-Yvette, France

<sup>ad</sup> Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

\* Deceased